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SUBJECT: FINAL PERFORMANCE REPORT TO Dr. Harold Weinstock, Program Director, AFOSR
GRANT: BIO-NANOTECHNOLOGY INFRASTRUCTURE AND TECHNOLOGY ORIENTED RESEARCH
Grant #: FA-9550-05-1-0232
Reporting Period: April 1, 2005- February 29, 2008

Principle Investigator: W. Kinzy Jones
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A. Dense Memory Devices

Statement of objectives

The key objectives of the proposal are: 1) understanding of the physics underlying the proposed concept of three-dimensional (3-D) magnetic recording and memory, 2) development of various mechanisms to record and read data in a 3-D magnetic system, 3) development of experimental methods to study properties of a 3-D magnetic system, 4) dissemination of the accomplishments through filing patents, publishing refereed papers and presenting at international conferences and meetings in the field, and 5) promotion of the proposed technology via the increased interactions with the industry and involvement of researchers in other institutions.

Key Findings

a. Finding I: Development of a Novel Mechanism to Study 3D Patterned Media via Spinstand Measurements

Among the key accomplishments with this system is the development of a novel measurement technique based on the Spinstand characterization of patterned recording media including 3D media in general (as described in the previous year report) and the multilevel form of 3D media particularly.

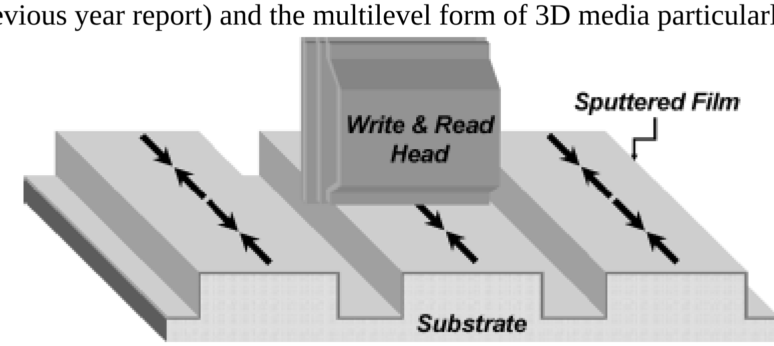

Figure 1 Illustration of a DTR medium showing the land and groove structure patterned into a NiP-plated, AlMg substrate.

b. Finding II: MFM Study of 3D Recording

Samples of 3D patterned media fabricated via FIB according to the above methods have been further studied via magnetic force microscopy (MFM). Nissim Amos is the key graduate student involved in this study.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
FIU research concentrated in the following areas of development: nanoelectronics, bio-nano sensors, and nanomaterials, processes, and characterization Five projects were supported: next generation information storage devices-both three-dimensional magnetic and protein-based, high power cold cathodes for microwave generators, carbon nanotube-based bio-sensors, silicon/polymer nanophotonics, and doped nanodiamonds and nanoceramic lasers for future devices. In magnetic storage devices, this work has resulted in patterned soft underlayer metallizations to localize the recording and sensitivity fields in 3-D recording media and the developement of a prototype using focused ion beam nanomachining to manufacture a 3-D magnetic system including a 3-D patterned media and magnetic transducer. In microwave generators, demonstrated thin-multiwall carbon nanotubes (tMWNTs) with low turn-on field (~0.5 V/μm) and stable operation and synthesized multistage tungsten oxide field emitters with high emission current (~180 μA/1tip). Demonstrated two electron multiplier concepts using both alumina continuous multiplier and a low temperature cofired ceramic (LTCC)/Ag dynode structure. Demonstrated both an ultra-small Si ring resonators characterized by a 2 μm radius on a single ring , with a free-spectral range of 50 nm or 6THz and an operating wavelength of 1510-1610nm and a silicon Horizontal Slot waveguide coupler with approximately 80% fiber-chip efficiency.

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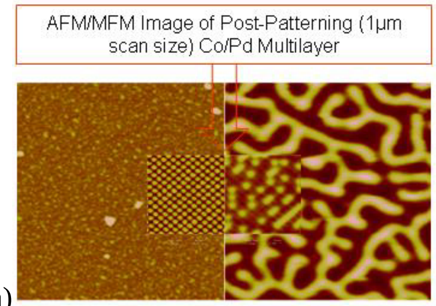
(a) 

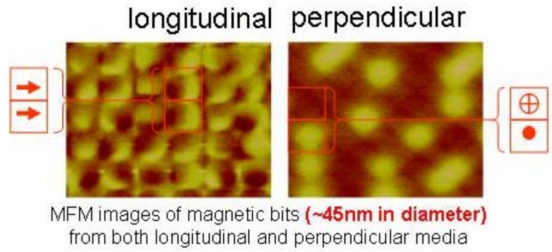
(b) 

Figure 2 (a) AFM and MFM images of a media before patterning. The insert illustrates the effect on the magnetization of FIB patterning (with a bit size of the order of 45 nm). (b) A schematic of the "GoogleEarth" concept used to navigate over a 2.5" disk with a 25-nm accuracy.

c. Finding III: Patterned Soft Underlayer and Interlayers

Throughout this effort, a new concept of patterned soft underlayer (PSUL) and interlayers (PSUI) was introduced. A patent was filed two years ago [[1]]. The concept was described in detail during the last year progress report. The schematics in Figure 3 illustrate the concept of bringing the image of a recording head closer to the recording media if a convex soft underlayer is used. Using a PSUL is equivalent to using a periodic array of images. In this case, each image effectively generates its own field. If the presence and arrangement of images could be controlled, this concept could be used to control the recording and sensitivity fields (used for recording and reading information, respectively) across 3D recording media. To summarize, the key advantages are:

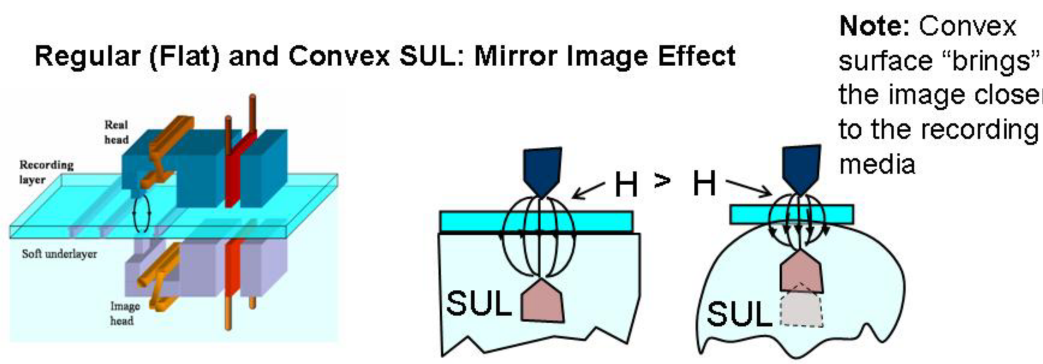


Figure 3

- PSUL increases the recording field across the thickness by at least a factor of two. PSUIs further increase the number of accessible layers across the thickness by at least a factor of three.
- PSUL and PSUI increase the recording field gradient across the thickness of a 3D recording media thus promoting ultra-high density recording

B. High Power Cold Cathode for Microwave Generator:

Accomplishments:

We have synthesized carbon nanotube (thin-MWNT on MWNT, figure 4) and tungsten oxide nanowire (nanowires on sharp tungsten tips) multistage field emitters (figure 5). Presences of nanoprotrusions such as nanowires or nanotubes on large feature size are defined as multistage structure/geometry. It has been observed from our experiments that multistage lowers threshold filed for emission due to increased field enhancement factor and also increases emission current. Figure 1a shows the well aligned and spaced multistage nanotube arrays grown on porous silicon, which can minimize the field screening effect thus resulting in improved emission.

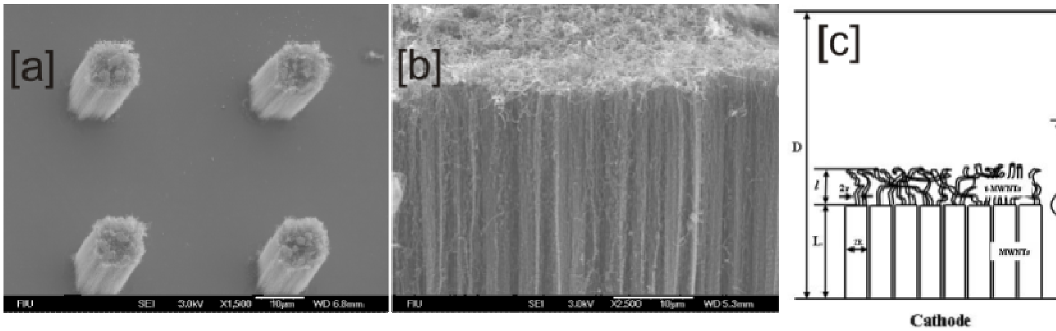


Figure 4. (a) Aligned and well spaced MWNT arrays (b) multistage nanotubes thin-MWNT on MWNT (b) multistage and field emission measurement schematic.

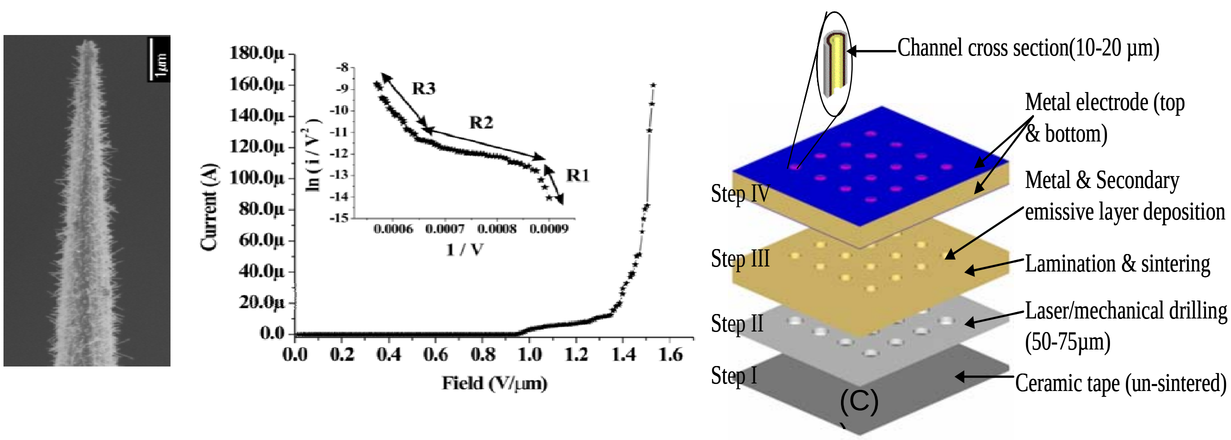


Figure 5. (a) Tungsten oxide (W18O49) nanowires grown on sharp tungsten tips (b) Field emission measurements i.e. applied field vs. current, (c) Schematic of assembling process of the CNT-MCP high power field emission system [1].

Figure 5a shows the SEM image of tungsten oxide multistage emitters and 3b its field emission measurements which showed ~170 μA per single tip with a threshold field of 0.97 V/μm. This is the highest current reported to date for tungsten oxide. Since oxide materials are chemically inert, robust and have relatively high melting temperature which leads to their stability in oxygen and low vacuum conditions i.e. 10^{-4} to 10^{-5} Torr. These emitters also demonstrated emission in various vacuum; it also shows the emission recovery measurements. This multistage design provides emitters capable of producing high field emission current operating at relatively low voltages thus improving the vacuum microelectronic devices performance.

In addition to the high temperature cofire ceramic (HTCC) multiplier demonstrated, a low temperature cofire ceramic (LTTC) electron multiplier with integrated cooling structure in a dynode configuration was also demonstrated. A capillary cooling structure based on Murray's law was designed and processes developed to provide 50 µm minimum X-Y-X channels in the ceramic using a nano-carbon fugitive filler. Z- axis channels for the multilayer structure of LTCC and thick silver re3quired for the dynodes multiplier structure were demonstrated with a diameter of 85 µm , along with the electrophoretic deposition of MgO on the cofired silver dynodes

C. Modeling, Design and Synthesis of CNT-based Bio-Nano Sensors:

Objectives:

- Surface modification of carbon nanotubes for specific analyte detection
- Label-free identification of biological element at the single molecule level

Accomplishments/New findings:

1. Surface modification of carbon nanotubes

(i) Surface modification by hydrophilic polymer In this project, single-walled and multi-walled carbon nanotubes (SWNT & MWNT, respectively), grown on oxide-coated silicon substrates using chemical vapor deposition, were modified with biocompatible polymer and enzymes.

(ii) Surface modification by specific enzyme immobilization of the specific enzyme (glucose oxidase, cholesterol oxidase etc.) was done by physical adsorption method on a modified MWNT surface

2. Detection of metabolites in human blood

The possibility for a real time quantitative analysis of the blood constituents through the use of electrochemical detection method has been demonstrated. We have demonstrated our capability of detecting glucose and cholesterol in buffer solution as well as in whole blood. The success of this venture would not only enhance the clinical applications, but also gives impetus to enter new areas of research including detection of toxins and drugs, relevant to Air Force missions.

3. Label-free identification of toxins at the single molecule level

We have dedicated the past one year trying to develop new sensor approaches for detecting the presence of biological toxins. With the Human Genome Project in the spotlight and genomic-based medicine looking to see what genes are expressed in healthy versus diseased tissues, these findings will guide therapy and research dealing with those diseases. It can also be exploited for precise identification of suspected anthrax strains and other pathogens which is included in AFOSR's mission for enhanced biosecurity

D. Silicon/Polymer Nanophotonics

- Nanoscale Opto-Electro-Mechanical Systems (NOEMS) have been demonstrated, which integrate microcantilever sensors with optical waveguides. (Fig 6(a,b))
- Microheaters integrated on chip have been simulated, fabricated and applied to the tuning of microring resonators filters which have allowed the wavelength division multiplexing of thousands of on-chip sensors. Spectral tuning range of the devices was 6 nm. (Fig 6(c))

(a) (b) (c) (d) (e)

Fig 6 (a) Metal electrodes on NOEMS cantilevers; (b) silicon cantilevers prior to release for cantilever biosensor; (c) Microring resonators with integrated heaters for multiplexing integrated sensors (such as cantilevers); (d) Ultra-small silicon ring-resonator; (e) High-concentration of field on the air for a silicon slot-waveguide photonic crystal waveguide resonators sensors.

- Ultra-small ring resonators with radius of 2um and the widest measured free-spectral range of 47 nm reported to date were fabricated and characterized. This device enables single ring resonators to be used with on-chip Er+-based amplifiers since only a single resonance is present in the gain bandwidth. (Fig 6(d))
- New silicon horizontal-slot waveguide devices based on photonic crystals were proposed that open the way for sensor integration into silicon platforms due to the high-field in the air-cladding, suitable for air-borne targets. This also paves the way for efficient lasers on silicon chips. (Fig 6(e))
- Micro-optical 1D DBR reflectors based on polymer materials have been fabricated (Fig. 7.a) and tested. The device is optically characterized by measure the spectrum of output. The single waveguide DBR which has five gaps is tested. The transmission of BOE-etched waveguide DBR shows a U-sharp centered at 1560nm (Fig7.b), which is the central wavelength of the band-gap in our single DBR design. Full 3D FDTD simulations indicate the possibility of reflectivities up to 97%, leading to the possibility of lasing action with suitable gain media. (Fig 7(c))

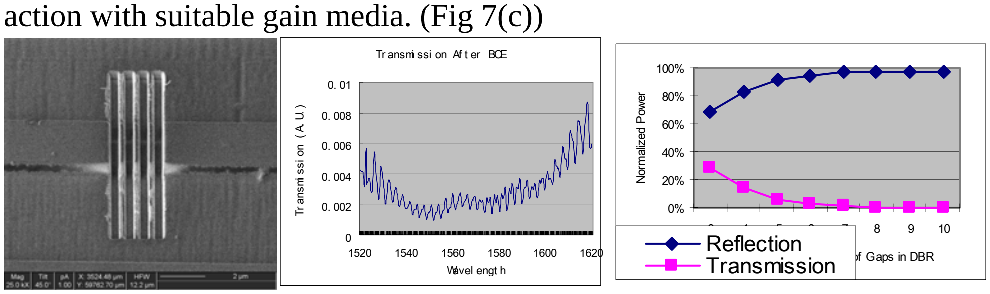


Fig. 7. (a) SEM picture of single DBR with five air gaps by FIB lithography; (b) Measurement of the optical transmission of air-clad waveguide DBR with (c) FDTD simulations of reflectivity of DBR devices.

- Novel polymer micro-opto-mechanical grippers have been developed that will enable the optical characterization while simultaneously manipulating micro and nano-scale objects. These devices will enable advances in microlaser assembly and biosensor development. These unique polymer microgripper devices were designed and manufactured in our labs to enable the micro-manipulation of micro/nano particles for integration into Microsystems.

These microgripper devices are also able to manipulate cells and other biological entities. Currently the devices can manipulate structures such as cells with dimensions in the 5-30 um range. (See Fig. 8).

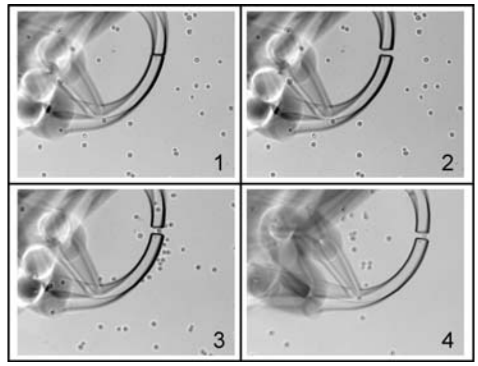


Fig 8. Manipulation of a single SKOV-3 cell utilizing a 50 μm wide arm microgripper. 1) gripper closed, 2) gripper opens, 3) cell is approached and grasped, 4) cell is moved and

E. Doped Nanodiamonds and Microchip Nanoceramic Lasers for Future Devices.

Use of gas-loading system to pressurize a sample chamber with different composition fluids: a three stage gas loading system has been installed. Any gases or mixtures of gases, including hydrogen, can be used to create pressures from a few bars to several kilobars surrounding a sample such as a nanopowder of diamond.

Uppsala University awarded the Rudbeck Medal in January 2007 to Dr. Surendra Saxena, professor emeritus of theoretical geochemistry at Uppsala University and now active at Florida International University in Miami. Dr. Saxena was awarded the medal for his extensive interdisciplinary and internationally acclaimed research on the nature of the Earth´s core.

The medal was instituted in 2002 on the 300th anniversary of the death of Olof Rudbeck, the elder. He was professor of medicine and, among other work, he discovered the lymphatic system, built the Anatomical Theater atop the Gustavianum building, and re-designed the layout of the city of Uppsala at the behest of Queen Christina. The medal is awarded for “outstanding academic work.” Recipients are selected by the Vice-Chancellor after consultation with the Vice-Rectors of the three Disciplinary Domains.

Books and Book Chapters:

1. S. Khizroev, R. Chomko, and D. Litvinov, chapter “Nanoscale Magnetic Devices” in Handbook of Semiconductor Nanostructures and Nanodevices, edited by A.A. Balandin and K.L. Wang, American Scientific Publishers, 2005; ISBN 1-58883-073-X
2. D. Litvinov and S. Khizroev, chapter “Nanomaterials and Nanodevices Synthesized by Ion-beam Technology,” Dekker Encyclopedia in Nanoscience and Nanotechnology, 2005; ISBN 0-8247-4797-6
3. Surendra Saxena, chapter “Phase transitions at high pressures:, in “Phase Diagram Determination” Elsevier Science 2006

Graduates Students involved in these thrusts

Dr. W. Kinzy Jones

1. Feng Zheng Graduate Research Assistant - (Doctoral Program)
2. Wenghong Wu Graduate Research Assistant- (Doctoral Program)

Dr. Sakhrat Khizroev

3. Nissim Amos, Ph.D.
4. Human Arjomandi, M.S., Summer 2006
5. Robert Cameron, M.S. Fall 2007, Hispanic American)
6. David Doria, M.S., Fall 2007, Hispanic American, currently engineer at Boeing Corporation
7. Nikhil Joshi, Ph.D., planned to graduate Fall 2007
8. Esnick Felissaint, M.S., FIU, Spring 2007, African American
9. Patricia Ange Fievre, Ph.D. student, Woman
10. Pablo Gomez, Ph.D., Summer 2006, FIU, Hispanic American, currently a PDF, UCR
11. Yazan Hijazi, Ph.D., Spring 2006, currently Assistant Professor, Puerto Rico
12. Rabee Ikkawi, Ph.D.
13. Derek Jacobs, Undergraduate Student, 2005-2006
14. Andrey Lavrenov, Ph.D., Spring 2007, currently a PDF, UCR
15. Kurt McKnabb, M.S., Summer 2006, FIU, African American, currently a Ph.D. student at FIU

Dr. Wonbong Choi

16. Dr. Somenath Roy, Coordinator, Research Program:
17. Raghunandan Seelaboyina, Graduate Research Assistant: (Doctoral program)
18. Harindra N. Vedala, Graduate Research Assistant: (Doctoral program)
19. Jun Huang Graduate, Research Assistant: (Doctoral program)
20. Ved Prakash Verma, Graduate Research Assistant: (Doctoral program)
21. Aparna Datta, Graduate Research Assistant: (Masters program)
22. Srinivas Rao Boddepalli, Teaching Assistant: (Masters program)
23. Michael Patterson, Teaching Assistant: (Masters program)

Dr. Roberto Panepucci

24. Magdalena Nawrocka, Post Doctoral Program - 05/06
25. Xuan Wang PhD, start Summer’04 -– Fabrication of Cantilever Silicon Waveguide Biosensor
26. Tao Liu PhD, start Fall’04 -– Nanophotonic structures in Polymer/Nanoparticle systems
27. Ange M. P. Fievre, PhD, start Fall’06 –. Nanoscale Slot Waveguide Structures
28. Jose Martinez, PhD, Spring'08 — Polymer Waveguide Microgripper
29. Ange M. P. Fievre, M.S. Apr’06 - – currently pursuing PhD in group.

Dr. Surendra Saxena

30. S.Venilla Raju, Post Doctoral Program
31. Andriy Durygin, Post Doctoral Program

Interactions With the Industry

Via the active participation of Song Xue, Executive Director, Advanced Transducer Development, Seagate Technology, the research efforts have been extensively exposed to the industry. These industry related activities include:

1. Opportunities for summer internships for undergraduate and graduate students to Western Digital, Seagate, Motorola, Hitachi
2. Joint research projects with the industry: 1) Mutlilevel Magnetic Recording, with Michael Alex, Hitachi Global Storage Technologies, 2) Imprint-based Patterned Media, with Nikhil Joshi, Motorola, 3) 3D Magnetic Recording, with Song Xue, Exec. Director, Advanced Transducer Development, Seagate, 4) Patterned Soft Underlayers, with William Cain, VP, Western Digital, 5) Nanomagnetic Probes for Ultra-high Density Information Storage, with Bin Lu, Media Manager, Seagate Technology, and others
3. Several graduate students routinely spent a week at the Guzik facilities, San Jose, California, to obtain direct training to operate the Spinstand Guzik V2002 according to the tightest industry requirements to a recording system.

Archival Publications (Published) During the Reporting Period

1. V. Parekh, D. Smith, Chunsheng E, J. Rantschler, S. Khizroev, D. Litvinov, "He+ ion irradiation study of continuous and patterned Co/Pd multilyaers," *J. Appl. Phys*. **101**, 083904 (2007).
2. P. Gomez, D. Litvinov, and S. Khizroev, "A method to design high SNR nanoscale magnetic sensors using an array of tunneling magneto-resistive (TMR) devices," *Journal of Physics D: Applied Physics*, 40, 4396-404 (2007)
3. Chunsheng E, J. Rantschler, S. Zhang, D. Smith, V. Parekh, S. Khizroev, D. Litvinov, "Integranular interactions of low temperature atmosphere annealed Co/Pd magnetic multilayers," *J. Appl. Phys.* **101**, 09D108 (2007)
4. V. Renugopalakrishnan, S. Khizroev, H. Anand, L. Pingzuo, L. Lindvold, "Future memory storage technology: protein-based memory devices may facilitate surpassing Moore's Law," *IEEE Trans. Magn*. **43** (2), 773-5 (2007)
5. (invited) S. Khizroev, Y. Hijazi, N. Amos, E. Felissaint, N. Joshi, R. Ikkawi, R. Chomko, and D. Litvinov, "Physics of Perpendicular Recording with a Patterned Soft Underlayer," special information technologies issue, *J. Nanoscience and Nanotechnology* **7**, 243-54 (2007)
6. N. Amos, A. Lavrenov, P. Gomez, R. Chomko, F. Candocia, D. Litvinov, S. Khizroev, "Nanomagnetic probes to image patterned media for information densities above ten terabit-per-square-inch," *J. Nanoelectronics and Optoelectronics* **2**, 1-3 (2007)
7. D. Smith, Chunsheng E., S. Khizroev, D. Litvinov, "The influence of bit patterned medium design and imperfections on magnetoresistive playback," *IEEE Trans. Magn*. **42** (10), 2285-7 (2006)
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10. Chunsheng E, D. Smith, J. Wolfe, D. Weller, S. Khizroev, D. Litvinov, "Physics of patterned magnetic medium recording: design considerations," *J. Appl. Phys.* **98** , 024505 (2005)
11. S. Khizroev, R. Chomko, Y. Hijazi, S. Mukherjee, R. Chantrell, X. Wu, R. Carley, D. Litvinov, "FIB-fabricated nanoscale magnetoresistive sensor," *Appl. Phys. Lett.* **86**, 42502 (2005)
12. (invited) D. Litvinov, S. Khizroev, "Perpendicular recording: playback," *Appl. Phys. Reviews – Focused Review*, *JAP* **97**, 071101 (2005)
13. Wonbong Choi, Do-hyun Kim, Young-chul Choi, and Jun Huang, "Y-junction single-wall carbon nanotube electronics", Journal of Materials March 44 (2007)

14. Jun Huang; Do Hyun Kim, Raghunandan Seelaboyina; Banglore K. Rao; Dake Wang; Minseo Park, WonBong Choi, “Catalysts effect on single-walled carbon nanotube branching”, Diamond and related materials, 16(8), 1524-1529 (2007)
15. Do-Hyun Kim, Jun Huang, Hoon-Kyu Shin, Somenath Roy, Wonbong Choi, “Transport Phenomena and Conduction Mechanism of Single-Walled Carbon Nanotubes (SWNTs) at Y- and Crossed-Junctions”, Nanoletters, 6(12), 2821 -2825 (2006)
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17. Raghunandan Seelaboyina, Jun Huang, Jucheol Park, Dong Hun Kang and Won Bong Choi, “Multistage field enhancement of tungsten oxide nanowires and its field emission in various vacuum conditions”, Nanotechnology 17 4840-4844 (2006)
18. Raghunandan Seelaboyina, Jun Huang, and Won Bong Choi, “Enhanced field emission of thin multiwall carbon nanotubes by electron multiplication from microchannel plate”, Appl. Phys. Lett. 88, 194104 (2006), Virtual Journal of Nanoscale Science & Technology, 13(21) 2006
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23. T. Liu and R.R. Panepucci, “Confined waveguide modes in slot photonic crystal slab”, Optics Express, Vol. 15, 4304-4309, 2007.
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